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Establishment Criteria For Integrated Wind Shear Detection Systems:

Low-Level Wind Shear Alert System (LLWAS), Terminal Doppler Weather Radar (TDWR), and Modified Airport Surveillance Radar

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16. Abstract

This report presents an integrated, site-specific, benefit-cost analysis of three wind shear detection systems: the low-level wind shear alert system (LLWAS), terminal doppler weather radar (TDWR), and airport surveillance radar modified for wind shear detection. Based on this analysis, a benefit-cost investment decision model has been developed. This investment decision (criteria) model will be incorporated into FAA-APO's Aviation Data Analysis (ADA) System and will be published in FAA Order 7031.2C, **Airway Planning Standard Number One** (APS-1).

Application of the establishment criteria documented in this report will enable the FAA to prioritize alternative investments among wind shear detection equipment types as well as sites, so as to maximize the return on investment dollars. For purposes of APS-1 criteria, FAA towered airports with a net present value (NPV) of zero or greater for a particular wind shear detection system will be considered establishment candidates for that system. If more than one system yields an NPV greater than or equal to zero at a particular site, then the one with the highest (positive) NPV is recommended for that site.

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EXECUTIVE SUMMARY

This report presents an integrated, site-specific, benefit-cost analysis of three wind shear detection systems: the low-level wind shear alert system (LLWAS), terminal doppler weather radar (TDWR), and airport surveillance radar (ASR) modified for wind shear detection. Net present value (NPV), or benefits less costs, is the analytical tool used to rank order competing wind shear detection systems. Based on the analysis, a benefit-cost investment decision model has been developed. This investment decision (criteria) model will be published in FAA Order 7031.2C, **Airway Planning Standard Number One** (APS-1). APS-1 is a working order which contains the policy and summarizes the criteria used in determining eligibility of terminal locations for establishment, discontinuance, and improvements of specified types of air navigation facilities and air traffic control services under the FAA's Facilities and Equipment Appropriation. ADA, a computer system developed and maintained by the Office of Aviation Policy and Plans, facilitates APS-1 processing through its benefit/cost subroutines and supporting 4,000-plus airport database of descriptive as well as historical and forecast aviation activity data. The establishment criteria developed in this report also fulfill corresponding requirements for such criteria by the Integrated FAA Wind Shear Program Plan.

The primary benefit of LLWAS, TDWR, and modified airport surveillance radar is reduced risk and expected incidence of wind shear-related accidents. Wind shear poses an infrequent but highly significant hazard to aircraft during takeoff and landing. The need for effective wind shear detection and reporting is evident from NTSB accident records. From 1964 through 1985, wind shear was identified as a cause or contributing factor in 80 accidents at FAA towered airports in which 576 lives were lost. Of these, 49 accidents and 434 fatalities occurred from 1975 through 1985. A secondary benefit afforded by wind shear detection systems is more effective planning of airport operations, by providing gust front and wind shift information to air traffic control personnel.

For purposes of APS-1 criteria, FAA towered airports with a net present value (NPV) of zero or greater for a particular wind shear detection system will be considered establishment candidates for that system. If more than one system yields an NPV greater than or equal to zero at a particular site, then the one with the highest (positive) NPV is recommended for that site.

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CHAPTER I - INTRODUCTION

A. Overview

Effective management and decisionmaking of capital investments in the National Airspace System requires, among other considerations, analysis and comparison of benefits and costs. FAA evaluates many of its investments in terminal navigation aids, communication aids, and air traffic control services by applying standard establishment and discontinuance "criteria." These criteria are summarized in FAA Order 7031.2C, Airway Planning Standard Number One - Terminal Air Navigation Facilities and Air Traffic Control Services (APS-1) (Reference 1). APS-1 is a working order which contains the policy and summarizes the criteria used in determining eligibility of terminal locations for establishment, discontinuance, and improvements of specified types of air navigation facilities and air traffic control services under the FAA's Facilities and Equipment Appropriation. For less expensive facilities and equipment, the criteria are normally expressed in terms of simple traffic activity thresholds. More expensive facilities and equipment are normally supported by investment criteria based on more complex benefit versus cost considerations. A complete discussion of benefit/cost analysis, as applied to FAA investment and regulatory analyses, may be found in Economic Analysis of Investment and Regulatory Decisions - A Guide (Reference 2).

This report presents an integrated, site-specific, benefit-cost analysis of three wind shear detection systems: the low-level wind shear alert system (LLWAS), terminal doppler weather radar (TDWR), and airport surveillance radar (ASR) modified for wind shear detection. Net present value (NPV), or benefits less costs, is the analytical tool used to rank order competing wind shear detection systems. Based on the analysis, a benefit-cost investment decision model has been developed. This investment decision (criteria) model will be published in APS-1 and incorporated into the Aviation Data Analysis (ADA) System. ADA is a computer system developed and maintained by the Office of Aviation Policy and Plans which facilitates APS-1 processing through its benefit/cost subroutines and supporting 4,000-plus airport database of descriptive as well as historical and forecast aviation activity data. The establishment criteria developed in this report also fulfill corresponding requirements for such criteria by the Integrated FAA Wind Shear Program Plan.

B. Organization of Report

The remainder of this chapter reviews the nature of low-altitude wind shear (including its hazard to aviation), the sources of wind shear, and FAA wind shear programs, systems, and services. This background provides a basis for understanding and appreciating the benefits provided by wind shear detection equipment. Chapter II gives an overview of the establishment criteria logic. Chapter III delineates the algorithms used to quantify site specific safety and efficiency benefits for LLWAS, TDWR, and modified ASR, and Chapter IV summarizes the life cycle costs of these systems. The results of applying the criteria to all FAA towered airports are presented in Chapter V.

C. The Nature of Low-Altitude Wind Shear

1. The Hazard Posed by Low-Altitude Wind Shear

Wind shear, any rapid change in wind direction or speed over a relatively short distance, has historically been a problem for aviation. Abrupt changes in wind direction or speed can cause sudden changes in the flow of air over an aircraft's wings and other lifting surfaces. These changes can affect an aircraft's flight characteristics so quickly and drastically that an aircraft's pilot may not be able to respond in time to prevent an accident if these changes occur close to the ground. Thus, wind shear poses a significant hazard to aviation, particularly in the lowest 1,000 feet of the atmosphere, the zone that an aircraft must penetrate while landing or taking off.

Aircraft accidents resulting from wind shear during takeoffs and landings have become a major source of concern in aircraft safety. The need for effective wind shear warning and detection and avoidance systems is evident from National Transportation Safety Board (NTSB) accident records. Table I-1 provides summary data of wind shear-related accidents involving scheduled commercial aircraft at FAA towered airports from 1975 through 1985. During this period, wind shear was identified as a cause or contributing factor in 49 accidents which resulted in 434 fatalities, 189 injuries. and 45 destroyed or substantially damaged aircraft. Disaggregate data on these accidents are presented in the Appendix.

Figure I-1 displays a geographic distribution of wind shear accidents as well as the mean number of days per year with thunderstorms, on a U.S. regional basis. Thunderstorms represent the closest form of recorded severe weather activity that is correlated with the presence of wind shear and therefore are a significant determinant in wind shear-related accidents. Since higher activity levels expose more aircraft to wind shear events, wind shear-related accidents are also correlated with traffic activity levels. Given the projected growth in future air traffic activity, the probability of a wind shear induced accident can be expected to increase in the future in the absence of improved wind shear detection and avoidance measures.

TABLE I-1. FAA Towered Airport Wind Shear Accident Data, 1975 - 1985 a/

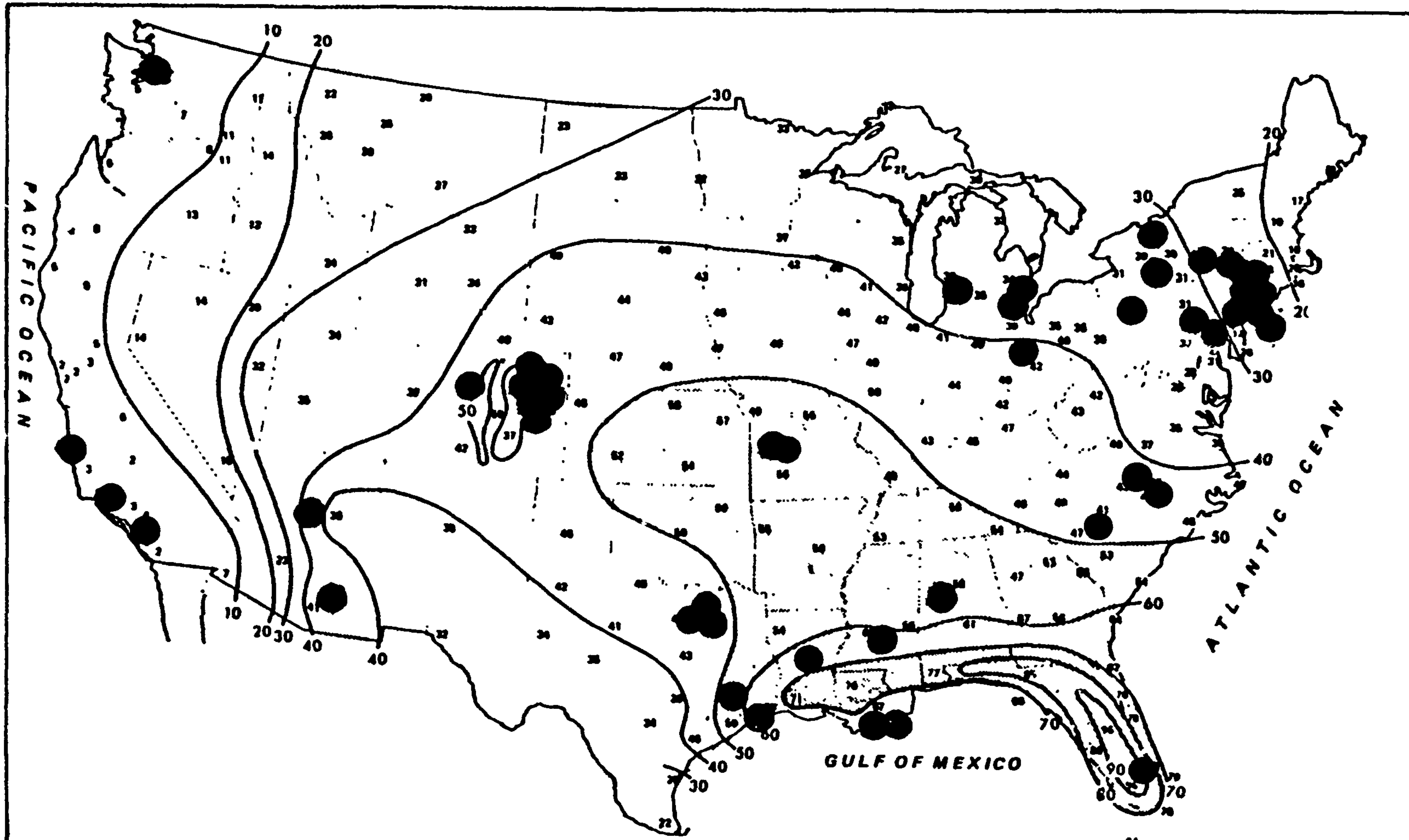
	Number	Total Cost Distribution	Operations (millions)	Rate/10 Million Operations
Accidents	49			0.762
Injuries:				
Fatalities (.304/Occupant)	434	87.0%		6.750
Serious Injuries (.106/Occupant)	151	1.6%		2.3[illegible]
Minor Injuries (.027/Occupant)	38	0.2%		0.591
None (.564/Occupant)	806	0.0%		12.536
TOTAL OCCUPANTS	**1429**	**88.8%**		
Aircraft Damage:				
Destroyed Aircraft (.388/Aircraft)	19	7.6%		0.296
Substantially Damaged Aircraft (.531/Aircraft)	26	3.6%		0.404
Minorly Damaged Aircraft (.061/Aircraft) b/	3	0.0%		0.047
None (.020/Aircraft)	1	0.0%		0.016
TOTAL AIRCRAFT	**49**	**11.2%**		
TOTAL		**100.0%**	**643.0**	

a/ See Appendix A for detail
b/ Minorly damaged aircraft are assumed to be insignificant and are assigned a u[illegible] loss of zero

FIGURE I-1

Mean Number of Days per Year with Thunderstorms (1951-1975) and
Geographic Distribution of Wind Shear Accidents at FAA Towered Airports (1975-1985)

(Numbers = T-Storm Days Per Year; ● = Accident)



49 total accidents. Not pictured: Fairbanks, AK; Kodiak, AK; San Juan, PR.

2. Sources of Low-Altitude Wind Shear

a. Introduction

The primary sources of low-altitude wind shear include: outflows (including microbursts) associated with thunderstorms and other convective clouds, gust fronts, and air mass fronts. Other sources of wind shear include: sea breeze fronts, terrain-induced wind shear, low-level jet streams, and high-speed atmospheric vortices. Table I-2 categorizes 30 of the 36 scheduled commercial wind shear-related accidents/incidents that occurred from 1964 through 1985 at FAA towered airports by wind shear source. As shown in the table, a majority of these accidents were caused by convective outflows (thunderstorms, ordinary showers, and microbursts).

b. Convective Outflows/Microbursts

Thunderstorms and other convective clouds are the most significant sources of low-altitude wind shear. These weather phenomena may produce strong downdrafts which transport air downward and induce outbursts of damaging winds at or near ground level. An estimated 90 percent of significant operational low-altitude wind shears are convectively induced (Reference 3). As illustrated in Figure I-1, thunderstorms occur most frequently in Florida, along the Gulf of Mexico coast, and over the central regions of the United States.

A convective microburst is a small downburst less than 2.5 miles in outflow size, which may reach the ground or dissipate in midair, with peak winds lasting two to five minutes. Based on the FAA's participation in the Joint Airport Weather Study (JAWS) and the FAA-sponsored Classify, Locate, and Avoid Wind Shear (CLAWS) projects (1982-1984), and other wind shear research, microbursts are believed to pose the most serious form of wind shear hazard to aviation safety. During the past several years, the aviation and scientific communities have gained considerable knowledge about microbursts. Nevertheless, fully understanding the nature of microbursts, explaining the forces that create microbursts in some thunderstorms but not in others, predicting their occurrence and location, and detailing appropriate pilot strategies when encountering a microburst, is still subject to future research.

c. Gust Fronts

While microbursts and other convective outflows are believed to pose the most serious wind shear hazard to aviation, gust fronts are also significant hazards. A gust front is the leading edge of a mass of cool air that has recently descended from a thunderstorm or convective cloud. Cool air near the gust front, which may be up to one mile in depth, is characterized by strong turbulent winds. The cool air sinks, while the warm air rises. The depth of the gust front and its speed of advance over the ground depend on the nature of the parent cloud and the wind distribution through the layer in which the cloud is embedded. When the winds are light and change little with altitude,

TABLE I-2. Sources of Wind Shear in Wind Shear-Related Accidents/Incidents at FAA Towered Airports Involving Scheduled Commercial Aircraft, 1964-1985

Month >	7	12	3	1	2	6	12	1	5	7	12	3	6	7	10	11	12	1	12	6	6	8	11	11	12	6	6	8	5	7	7	12	12	5	6	8	Total	
Day >	1	24	17	23	27	8	10	4	18	26	12	3	15	23	23	27	17	30	14	24	24	7	12	29	31	23	3	22	21	9	28	5	28	31	13	2		
Year >	64	64	65	66	66	68	70	71	72	72	72	73	73	73	73	73	73	74	74	75	75	75	75	75	75	76	77	79	82	82	82	82	83	84	84	85	No.	%
																					Inc							Inc			Inc							
Convective Outflow																																						
Thunder Shower	X			X		X			X	X		X	X	X		X			X	X	X	X		X		X	X				X				X	X	19	53%
Ordinary Shower		X					X								X		X	X					X		X					X				X			9	25%
Microburst														X		X		X		X	X	X				X	X			X	X			X		X	12	33%
Gust Front/Microburst	X					X								X																							3	8%
Air Mass Front								X			X						X																				3	8%
Sea Breeze Front																				X	X																2	6%
Terrain Wind Shear		X					X																														2	6%
Other or Not Avail			X		X																							X	X			X	X				6	17%
Fatalities	0	3	0	0	0	0	0	0	0	0	0	0	0	38	0	0	0	96	0	112	0	0	0	0	0	0	0	0	0	153	0	0	0	0	0	135	537	
Injuries	0	0	0	0	0	4	0	2	3	0	0	3	0	6	5	42	16	5	0	12	0	15	8	0	0	86	0	0	0	9	0	0	0	0	10	28	254	
Landing	L		L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	na		L	L	L	L		L	L		L	L	L		L	L	30	86%
Takeoff		T																			na	T					T			T				T			5	14%

Inc = incident
na = not available

Source: References 3,7,8,11,12,13 and NTSB Aviation Accident Data System

the gust front is almost symmetrical around the storm that produced it. By the time the storm has dissipated, the gust front may have moved miles away from the parent storm and weakened substantially. When there is strong vertical wind shear through the atmosphere and a severe long-lasting convective storm, the associated gust front tends to be maintained at the leading edge of the parent storm. The pattern of its advance can be very asymmetric with strong outward-blowing winds in those centers coinciding in direction with the strongest winds aloft in the cloud layer.

d. Air Mass Fronts

Separate air masses do not mix readily when they come into contact if they have different temperatures and humidities. Instead, the colder, more dense air mass passes under the warmer, less-dense air mass. The zone of transition between the two air masses is called a front. When the cold air advances, forcing the warm air to retreat and pass over the wedge of cold air, it is called a cold front. When the warm air advances, the frontal boundary moves toward the cold air and a warm front is said to exist. There usually is a sharp change of wind velocity across fronts and all fronts have some degree of wind shear across the zone of transition between the air masses.

Frontal conditions and the accompanying wind shears occur in all regions of the United States, but they occur most frequently over the middle latitudes during the colder months of the year. While Hawaii averages about two shears per winter, the central and northwest regions of the United States average four to five per month during the fall, winter and spring. The southern states and those east of the Rocky Mountains average one significant frontal passage per month during the same seasons.

e. Sea Breeze Fronts

A sea breeze is a local wind that blows from sea to land. It is caused by the temperature differences that occur daily between the sea surface and the adjacent land. Often, the onset of a sea breeze occurs suddenly as a sea breeze front, separating the cool air from the warm air, moves inland. Sea breeze fronts cause a sudden change in wind velocity, from near calm to a brisk cool breeze. Wind shear associated with sea breezes can be hazardous at airports located along coastlines.

f. Terrain-Induced Wind Shear

Mountainous terrain can cause significant low-altitude wind variability by inducing high-amplitude undulations or waves in air currents flowing over it. Airports located close to mountains, near breaks in mountain ranges, or on hills with sharp dropoffs near the ends of runways are subject to steady-state winds that often break down into constantly changing gusts. The presence of severe turbulence caused by mountain waves can compound the problem of operating aircraft in and out of these airports. Their influence can extend

from ground level to very high altitudes. It is not unusual to have gust velocities that double steady wind speeds. In extreme cases these gust velocities can exceed 100 knots. Wind shear induced by terrain occurs most often in the non-summer months. However, mountain waves have been observed during every month of the year in Alaska and in the western mountainous regions of the United States and Canada. In an average year, to the lee of the Rocky Mountains, in Montana and southern Canada, there are 15 wave days a month. In Colorado and in southern states there is an annual average of 7 wave days a month. The mountains in the eastern United States usually do not produce strong downdraft winds because their lee slopes are not particularly steep.

g. Low-Level Jet Streams

The strength of the wind near ground level is closely linked to diurnal processes on the lower atmosphere. During daytime the earth's surface is heated by the sun, and the planetary boundary layer is marked by vertical air motions. This process causes the frictional influence of the ground on the wind to be transmitted through a deep layer of air. Thus, wind velocities near the ground tend to be relatively high in the form of a concentrated current called a low-level jet stream. The formation of such a jet stream depends also on the distributions of heating and cooling and their daily variations over sloping terrains.

In a typical low-altitude jet stream situated over an airport, the wind at the surface tends to be light and to come from the same direction as the stronger flow immediately above the airport. Consequently, an aircraft that is landing will typically approach the runway into the jet stream wind. As the aircraft descends below the jet stream, headwinds decrease, often substantially, as the aircraft nears touchdown. The sudden loss of headwind can be a serious problem if the pilot is unaware of the situation. A typical low-altitude jet stream event often occurs in clear air but at night, when the visual perspective of a pilot may be inhibited.

h. High-Speed Atmospheric Vortices

No discussion of low-altitude wind shear would be complete without at least a mention of high-speed atmospheric vortices such as tornadoes, waterspouts and dust devils. Of these phenomena, tornadoes are associated with the strongest wind shears.

D. FAA Wind Shear Programs, Systems, and Services

1. Overview

Each element of the Integrated FAA Wind Shear Program will contribute to the overall safety of the National Airspace System.[*] Operational information on wind shear can currently be obtained from meteorological forecasts, pilot reports, and LLWAS (the latter exists at 110 airport sites). National Weather Service (NWS) products provide short and long-term planning capabilities and forecast guidance for many airports, including thunderstorm and other convective weather information. This information is supplemented by voluntary pilot report (PIREPS) of hazardous weather encountered in flight. Where available, LLWAS is used continuously to provide airport wind conditions. These sources of wind information are broadcast to all pilots in the area. In the future, information provided by LLWAS will be augmented by TDWR and modified ASR. In addition, some aircraft will be equipped with on-board present-position wind shear warning and guidance and control systems. If an aircraft has on-board sensors that detect hazardous wind shear, then an approach or departure will be aborted if the on-board detector sounds an alarm. If an equipped aircraft encounters a wind shear, then the on-board guidance and control systems (along with approved flight procedures) will provide flight crew with the best information to recover from the encounter. In this case, wind shear training will augment the flight crew's ability to escape a wind shear encounter. Further in the future, on-board "forward-looking" sensors will provide additional wind shear avoidance capabilities. Although outside the scope of low-altitude wind shear detection, next generation weather radar (NEXRAD) will be used to monitor weather conditions along flight routes.

By design, there is deliberate redundancy and complementarity among Integrated Wind Shear Program elements. Some degree of redundancy is essential to effectively deal with the multifaceted nature of the wind shear phenomenon. As discussed in the previous section, low-altitude wind shear can originate from a variety of sources and is often unpredictable. Redundancy of program elements helps insure against technical and schedule risks as well as operational failure of individual program elements. Data sources for wind shear information and the relationships between current and future FAA wind shear programs, systems, and services, are illustrated in Figure I-2.

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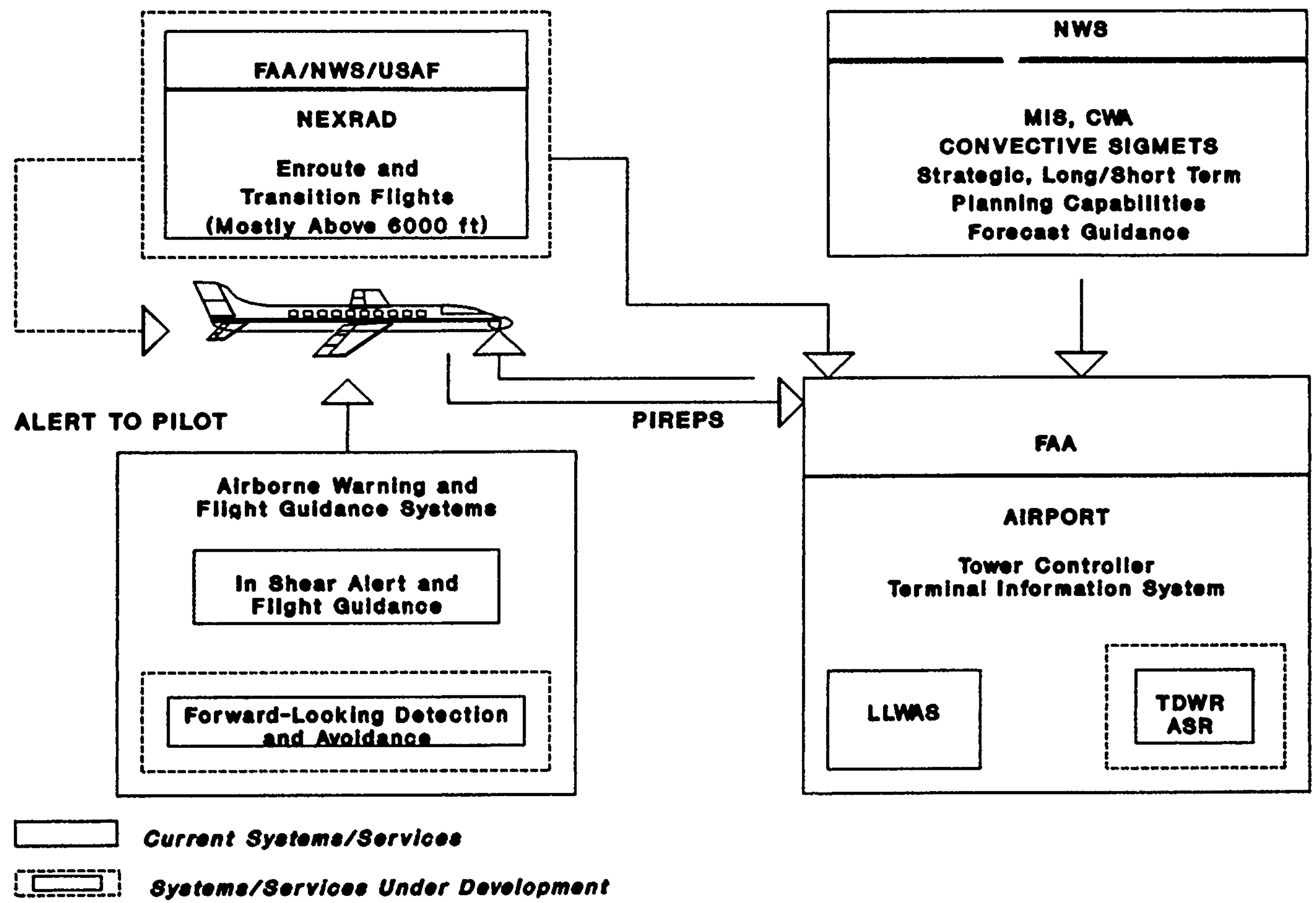
[*]The Integrated FAA Wind Shear Program (Reference 4) is a five-element plan comprised of: (1) ground-based detection equipment; (2) aircraft-mounted warning, detection, and avoidance equipment; (3) education, training and operating procedures; (4) terminal information systems for communicating wind shear information to pilots; and (5) further research into the nature of wind shear.

FIGURE I-2. Data Sources for Wind Shear Information - Current and Future



Source: Reference 4 and FAA program offices

2. Programs, Systems, and Services

a. National Weather Service

The National Weather Service (NWS) offers a wide variety of meteorological services, including forecasts and advisories provided to the FAA and the aviation community. The existing NWS network of weather radars detect rain, showers, thunderstorms, and other phenomena often associated with wind shear. The turbulence portion of the Aviation Area Forecast, prepared three times each day by the National Aviation Weather Advisory Unit in Kansas City, MO, indicates the likelihood of low-altitude wind shear. In addition, 52 Weather Service Forecast offices issue, at the same frequency, site-specific terminal forecasts, including the likelihood of low-altitude wind shear. These aviation weather notices are transmitted to FAA and NWS facilities as well as other facilities in the aviation community that have appropriate communications equipment. Currently, major airport traffic control towers receive briefings, forecasts, and nowcasts (conditions currently in existence or beginning within two hours) from Center Weather Service Units (CWSU) in their cognizant Air Route Traffic Control Centers (ARTCC), based on CWSU analysis and interpretation of NWS products. Scheduled and as-required briefings generally consist of a forecast of weather conditions pertinent to the ARTCC area during a specified period, plus an extended outlook.

Meteorological Impact Statements (MISs) give long range (4-12 hour) forecast capabilities for many major airports. Significant Meteorological Information Advisories (SIGMETS) are severe weather advisories issued in hourly and special bulletins. Convective SIGMETs are warnings of the most severe weather conditions. They are issued for tornadoes and very severe thunderstorms. SIGMETs are also issued for severe and extreme turbulence, icing, and widespread obstructions to visibility such as dust and sand. Airman's Meteorological Information Advisories (AIRMETs) are less extreme potential hazards to aircraft such as moderate icing conditions. Center Weather Advisories (CWAs) are unscheduled severe weather advisories. They are developed by Center Weather Service Unit meteorologists at FAA ARTCC's through analysis and interpretation of area forecasts, terminal forecasts, SIGMETs, pilot reports, and other sources of available weather information. CWAs may also supplement or redefine existing SIGMETs.

While the services discussed above have a positive impact on the overall weather information system, they do not satisfy all wind shear information requirements at the local airport level. Meteorological forecasts are of limited usefulness for predicting downbursts due to their short lifetime and random occurrence. At best, these forecasts warn flight crews and controllers of conditions conducive to generating downbursts and wind shear activity. Investigations in the Joint Airport Weather Study (JAWS) and analyses of the 1982 Pan American Airlines crash in New Orleans have demonstrated that accidents can occur in storms that are not considered severe. Despite their lack of small-scale detail, NWS information does alert pilots to the possibility of a wind shear encounter, reducing their recognition and reaction times should a wind shear event occur.

b. PIREPs

PIREPs are voluntary pilot reports of meteorological phenomena encountered in flight. They are an important source of information on immediate weather conditions along the approach and departure corridors, for both controllers and pilots. The reliability of this information is limited, however, because not all pilots provide PIREP data. Nonetheless, PIREPs of wind shear encounters are currently the only primary source of wind shear information for airports not equipped with LLWAS.

c. Education, Training, and Operating Procedures

This element of the Integrated FAA Wind Shear Program is an ongoing effort between industry, the academic and scientific communities, and the FAA. This will provide aviation users with appropriate education, training aids, and operating procedures for recognizing, avoiding, and recovering from hazardous wind shear conditions. Historically, a lack of definition in basic wind shear training objectives had caused widespread confusion and a certain degree of reluctance by many air carriers to adopt any formal wind shear training program. In an effort to fill this void, the FAA awarded a contract to the Boeing Company to develop a Wind Shear Training Aid. The basic training package, consisting of two volumes, 90 35 mm slides, and two videotapes, was delivered to the FAA in February 1987. The FAA has, in turn, provided copies of the Wind Shear Training Aid to several hundred airlines and related organizations for incorporation into their respective training programs.

d. Airborne Systems

In September 1988, the FAA issued a Final Rule which amended the Federal Aviation Regulations (FARs) Parts 121 and 135, by requiring that: (1) certain turbine powered airplanes operated under Part 121 be equipped with an approved airborne wind shear warning with flight guidance system; (2) all Part 121 operators conduct approved low-altitude wind shear flight training in a simulator; and (3) Part 121 and 135 certificate holders' training programs include flight crew on recognition of and escape from hazardous wind shear conditions (Reference 11).

There are two generic types of such systems: (1) present-position systems, which warn the flight crew that the aircraft is currently in or entering a wind shear condition and that recovery maneuvers must be initiated; and (2) forward-looking or predictive systems, which look ahead of the aircraft to provide the flight crew with wind shear avoidance capability. The FAA has already approved a number of present-position systems that constantly monitor various flight parameters to alert flight crews about wind shear encounters. Use of present-position sensors is becoming more widespread. Forward-looking systems are still undergoing development. The FAA has entered into a five-year cooperative agreement with the National Aeronautics and Space Administration (NASA) to develop the system requirements for present-position devices. Started in October 1986, this effort will continue through September 1991 and will rely on cooperation with industry to transfer the requisite technology. A certifiable forward-looking system is not currently envisioned before the mid-1990's.

e. Basic LLWAS

Originally developed in 1976 to detect large-scale events conducive to wind shear (such as those discussed in Section 2), the low-level wind shear alert system (LLWAS) is currently the only operational ground-based wind shear detection system in use by the FAA.

The system is a real-time, computer-controlled, surface wind sensor system which uses telemetry as a communications link and minicomputer processing to evaluate wind speed and direction from sensors on the airport periphery with centerfield wind data. "Basic LLWAS" consists of a six-station sensor array of wind speed and direction sensors with one station located at center field on the airport and the other five sensors nominally located around the periphery of the airport. The sensors are propeller vanes or anemometers mounted on poles that are sited to provide the best coverage of runway corridors with minimal interference from terrain and other wind obstructions. The center field site is considered a reference site for which a two-minute running average of wind velocity is maintained. Each site has a collateral Remote Wind Unit which maintains the wind data for the site and transmits it to the central processor when polled. The remote sites are polled at ten-second intervals by a central processor which compares the wind velocity at each of the five peripheral sites with the two-minute running average wind velocity at the centerfield site. Whenever the magnitude of the vector difference between the center field average wind and one or more of the peripheral sensors exceeds a specified threshold, visual and audible alarms are signaled in the airport traffic control tower. The wind velocities at center field and at the alarming sensor(s) are presented on the tower controller's display. During the time that the alert is posted, controllers provide wind shear advisories to all arriving and departing aircraft.

Basic LLWAS was installed at 110 FAA towered airports. Since this system was designed prior to the discovery of microbursts, it performs poorly at detecting this primary source of wind shear. Moreover, Basic LLWAS provides alert information in a form that is not optimal for pilot use (i.e., the pilot needs measurements of actual wind shear along approach/departure flight paths). Due to these system limitations as well as technological advances, the Basic LLWAS systems are being upgraded and or replaced by the FAA in two phases. First, all 110 systems will be upgraded to the Six Sensor Improvement LLWAS. The next phase will replace an existing LLWAS system with the Expanded Network LLWAS, for those sites where the benefits of such replacement exceed the costs.

f. Six Sensor Improvement LLWAS and Expanded Network LLWAS

The Six Sensor Improvement LLWAS (hereafter referred to as LLWAS-6) includes the basic system, with the following enhancements: high-capacity computers and advanced algorithms to improve the probability of wind shear detection; wind shear/microburst detection capability at centerfield; and data recorders to store wind data. The FAA began upgrading the Basic LLWAS systems to LLWAS-6 in 1988 and expects to complete this process in 1991.

LLWAS-6 has several limitations. While it exhibits reduced false alarm rates relative to the basic system, LLWAS-6 is, nevertheless, prone to false alarms. In addition, sparse station spacing may permit small-scale microbursts to go undetected by LLWAS-6.

Starting in 1995, FAA will replace LLWAS-6 systems with the Expanded Network LLWAS (hereafter referred to as LLWAS-EN), at sites where replacement is cost beneficial. The LLWAS-EN upgrades LLWAS-6 by adding up to 32 stations. Improved features of LLWAS-EN relative to LLWAS-6 include: 1. increased sensor density, allowing finer area resolution for microburst detection; 2. improved detection algorithms; 3. improved controller displays which provide improved transfer of alert information; 4. runway orientation information format; and 5. improved siting criteria and taller sensor poles to reduce wind sheltering. During the interim period, seven LLWAS Network Expansion systems will be installed at major hub airports to supplement the prototype Network Expansion systems already installed at Denver and New Orleans. These seven systems are scheduled to be installed in 1992.

g. TDWR

Recent advances in Doppler radar technology and algorithms for identifying and characterizing wind shear have demonstrated the potential of Doppler radar as the basis for a terminal wind shear and wind turbulence detection system. These advances have culminated in the scheduled implementation of the Terminal Doppler Weather Radar (TDWR) system by the FAA. TDWR will detect wind shear and turbulence associated with outflows, gust fronts, cold fronts, and other wind discontinuities in precipitation and in clear air. In addition, it is expected to detect weather phenomena or generate weather products such as precipitation intensity, movement of weather phenomena (e.g., windshift prediction and wind profiles).

The TDWR Project provides for the design, procurement, installation and implementation of 47 C-band frequency units - 44 operational units at or near high-activity airports that are most vulnerable to wind shear and support systems at the FAA Aeronautical Center, the FAA Technical Center, and Andrews AFB, respectively. Implementation is planned over the early-1992 - 1995 time frame. When wind shear conditions are present in the terminal coverage area, the TDWR System will generate information on the location and characteristics of the wind shear, and transmit this information via land line to the airport traffic control tower, In the tower, the information will be shown on two displays: (1) an alphanumeric display for use by air traffic controllers; and (2) a graphical situation display for use by air traffic control supervisory personnel.

On the controller display, the wind shear alert information will appear as a text message that can be quickly and easily read to aircraft pilots. As a result of the TDWR information, pilots can take precautionary measures to avoid areas where wind shear conditions exist. TDWR will also provide warning of sustained wind shifts and hazardous weather to air traffic control supervisory personnel to allow for improved planning of airport operation (e.g., runway shifts).

During the TDWR's initial operating phase, the controller will relay wind shear information verbally to pilots. Once the TDWR is operating in an end-state condition, the system will interface with the Terminal Control Computer Complex (TCCC) and the Area Control Computer Complex (ACCC), and hazardous weather information will be transmitted to pilots via data uplink using the Mode-S System.

During fall 1988, the TDWR prototype completed an operational test at Denver with very encouraging results. TDWR will provide coverage for detecting microbursts up to 1500 feet above ground level at a distance of six nautical miles (nmi) from the airport. Coverage for detecting gust fronts extends to 40 nmi from the airport. Whereas LLWAS systems measure winds in real time, TDWR is designed to provide a warning to pilots one minute prior to encountering a hazardous wind shear event (Reference 6).

h. ASR-9

Airport Surveillance Radar (ASR), a surveillance radar primarily tasked to detect aircraft in terminal areas, collects data that identifies aircraft location, altitude, airspeed, and flight number and displays the data on the controller's screen. The display is the controller's primary means of "seeing" and separating aircraft. In 1989, the FAA began replacing existing ASRs with ASR-9's (Ninth Generation), the latest state-of-the-art surveillance radars. In addition to improving surveillance, ASR has near real-time weather processing capabilities on an independent weather channel.

The Massachusetts Institute of Technology's Lincoln Laboratory has conducted extensive research concluding that with certain modification, ASR-9 would be an effective wind shear detector. These modifications would take place after initial production and installation of the ASR-9. The fast scan rate of 4.8 seconds per revolution provides timely data for detection processing. Since an ASR-9 is located on the airport, it may provide a better runway estimate of a wind shear than the off-airport TDWR. ASR-9 detection of microbursts and other hazardous wind shear events covers an area within 6.5 nmi of the radar (Reference 6).

i. Integrated Systems

Technology for complex data level integration of two or more wind shear detection systems is currently under development. In the complex data level integration, wind field data from LLWAS-EN would be interfaced in real time to the TDWR radar products group (RPG) for direct incorporation into the wind shear detection processing algorithms. Although integration of LLWAS-EN with TDWR is being actively pursued, LLWAS-EN integration efforts are not currently underway with ASR-9. For the dual-Doppler (TDWR-ASR-9) case, ASR-9 measurements would be sent, in real time, to the TDWR RPG for direct application in the wind shear processing algorithms.

Radar-LLWAS-EN combinations offer a variety of capabilities, including: protection against both clear air and high reflectivity wind shear phenomena, discrimination of microbursts occurring on the edge of the LLWAS-EN system, validation of possible false alarms, and providing airport runway-oriented wind information.

Dual-Doppler combinations provide complementary look angles for protection against asymmetrical microbursts and validation of possible false alarms. Better estimates of runway-oriented wind loss/gain information can be achieved with a dual-Doppler than with a single radar system.

The final configuration involves integrating all three wind shear systems. In this case, the dual-Doppler configuration would be established and then interfaced with LLWAS-EN. This configuration offers the collective capabilities of the radar-LLWAS-EN combination and the dual-Doppler combination.

Note: For ease of presentation in this report, system integration is denoted by a "+." For example, an LLWAS-EN integrated with a TDWR is presented as LLWAS-EN+TDWR.

CHAPTER II - ESTABLISHMENT CRITERIA

A. Overview

As stated earlier, effective management and decisionmaking of capital investments in the National Airspace System requires an analysis and comparison of relevant benefits and costs. FAA evaluates many of its investments in terminal navigation aids, communication aids, and air traffic control services by applying standard establishment and discontinuance "criteria." For less expensive facilities and equipment, the criteria are normally expressed in terms of simple traffic activity thresholds. More expensive facilities and equipment are normally supported by investment criteria based on more complex benefit versus cost considerations. The following Section describes the general criteria logic for candidate wind shear detection systems. The algorithms for estimating site-specific safety and efficiency benefits of the candidate wind shear detection systems are discussed in detail in Chapter III, while the costs associated with these systems are delineated in Chapter IV.

B. Criteria Logic

The criteria for wind shear detection systems are based on a comparison of the present value of the quantified benefits with the present value of quantified costs. Net present value (NPV), or benefits less costs, is the analytical tool used to rank order competing wind shear detection systems at a given airport site. For purposes of APS-1 criteria, FAA towered airports with an NPV greater than or equal to zero will be considered establishment candidates, i.e.,

$$NPV = BPV - CPV \geq 0,$$

where:

NPV = net present value of candidate system
BPV = present value of life-cycle benefits of candidate system
CPV = present value of life-cycle costs of candidate system

Both BPV and CPV are denominated in constant dollars. In addition, both benefits and costs are calculated incrementally to a "reference system." The reference system at an airport consists of the wind shear equipment already in place or contractually obligated at that site.

CHAPTER III - LIFE-CYCLE BENEFITS

A. Overview

FAA's investment criteria for wind shear detection equipment are based on two categories of benefits, described below:

- **Safety benefits** are derived from investments that reduce accidents or accident risk. Safety is the primary benefit provided by wind shear detection systems. Low-altitude wind shear presents an infrequent but highly significant hazard to aircraft on takeoff or landing and poses a hazard to all aircraft types - from small general aviation aircraft to wide-body jets. Effective detection and warning of wind shear conditions in terminal areas should result in the reduction of low-altitude wind shear accidents, and consequent reductions in fatalities, injuries, and property damage.

- **Delay (efficiency) benefits**, in the form of reduced aircraft variable operating costs and passenger time savings, are realized when an investment reduces flight delays, diversions, cancellations and overflights. Advance knowledge of wind shear conditions facilitates planning for efficient runway shifts which, in turn, promotes more efficient airport operation.

Note that for this study, benefits are calculated incrementally to a "reference system." The reference system at an airport consists of the wind shear equipment already in place or contractually obligated at that site.

B. Safety Benefits Algorithm

The algorithm used to estimate site-specific safety benefits as well as mnemonic definitions are presented in Figure III-1. Descriptions of key variable inputs to the safety benefits algorithm are discussed below.

1. Historic Accident Rates ($ACRATE_c$)

A variety of studies of aircraft accidents and incidents related to low-altitude wind shear have been conducted to date (References 3, and 7 through 13). Table III-1 summarizes the historical data on wind shear-related accidents from 1964 through 1985. For the present study, the 1975-1985 period was used to develop values for $ACRATE_c$, accident rates by user class. During this period, wind shear-related accident rates are 1.228×10^{-7}, 1.292×10^{-7}, and 0.601×10^{-7}, for the scheduled commercial, non-scheduled commercial, and non-commercial user classes, respectively. Appendix A gives a more detailed presentation of the wind shear-related accidents that occurred from 1964 through 1985 at FAA towered airports.

FIGURE III-1. Site-Specific Safety Benefits Algorithm

$$LCYSAF_s = \sum_{y=1}^{20} \{ ANNSAF_{s,y} \times (1 / (1 + d)^{y-0.5}) \}$$

$$ANNSAF_{s,y} = \sum_{c} \underbrace{\underbrace{ACRATE_c \times ANNOPS_{c,y} \times SWEF}_{\text{Expected Annual Gross Nr. of Accidents W/O Investment}} \times \underbrace{SEFF_s}_{\text{Portion Avertible}}}_{\text{Expected Annual No. of Averted Accidents}} \times \underbrace{ACCOST_c}_{\text{Expected Cost per Accident}}$$

$LCYSAF_s$	=	Discounted present value of life-cycle safety benefits of system "s" (constant dollars)
s	=	System under consideration
y	=	Year of system's operating life-cycle (assumed to be 20 years)
$ANNSAF_{s,y}$	=	Nondiscounted value of expected annual safety benefits of system "s" in year "y" (constant dollars)
d	=	Discount rate. Set at 10 percent in accordance with OMB guidelines (Reference 14)
0.5	=	Exponential factor to effect mid-period discounting
$ACRATE_c$	=	Historic wind shear-related accident rate per aircraft operation by user class "c"
$ANNOPS_{c,y}$	=	Forecasted annual number of aircraft operations by user class "c" in year "y"
SWEF	=	Site-specific safety weather exposure factor
$SEFF_s$	=	Safety effectiveness of system "s"
$ACCOST_c$	=	Expected site-specific cost of a wind shear-related accident for user class "c"

TABLE III-1. Summary of Historic FAA Towered Airport Wind Shear-Related Accidents and Rates

Year	Number of Low-Level Wind Shear Accidents 1/				Nr of Civil Aircraft Opns at FAA Towered Airports (Mill) 2/				Low-Level Wind Shear Accident Rate per 10 Million Operations			
	Schd Comm	Nonschd Comm	Noncomm	Total	Schd Comm	Nonschd Comm	Noncomm	Total	Schd Comm	Nonschd Comm	Noncomm	Total
1964	2	0	0	2	7.4	0.7	20.9	29.1	2.7	0.0	0.0	0.7
1965	1	0	1	2	7.5	0.9	23.6	31.9	1.3	0.0	0.4	0.6
1966	2	0	3	5	8.2	1.0	28.7	37.9	2.4	0.0	1.0	1.3
1967	0	1	0	1	8.6	1.3	34.5	44.3	0.0	8.0	0.0	0.2
1968	1	0	2	3	9.9	1.4	38.4	49.6	1.0	0.0	0.5	0.6
1969	0	0	2	2	10.7	1.5	40.3	52.5	0.0	0.0	0.5	0.4
1970	1	0	1	2	10.8	1.5	40.5	52.8	0.9	0.0	0.2	0.4
1971	1	0	0	1	10.1	1.3	39.4	50.7	1.0	0.0	0.0	0.2
1972	3	0	2	5	9.7	2.0	38.4	50.1	3.1	0.0	0.5	1.0
1973	6	0	0	6	9.8	2.1	38.8	50.7	6.1	0.0	0.0	1.2
1974	2	0	0	2	9.5	2.4	42.2	54.0	2.1	0.0	0.0	0.4
1975	5	0	4	9	9.4	2.7	44.2	56.2	5.3	0.0	0.9	1.6
1976	1	0	1	2	9.3	2.9	47.6	59.8	1.1	0.0	0.2	0.3
1977	1	0	1	2	9.8	3.3	51.0	64.0	1.0	0.0	0.2	0.3
1978	0	1	3	4	10.1	3.8	50.8	64.6	0.0	2.7	0.6	0.6
1979	0	1	3	4	10.4	4.4	51.7	66.5	0.0	2.3	0.6	0.6
1980	0	1	3	4	10.7	4.1	49.0	63.7	0.0	2.5	0.6	0.6
1981	0	1	4	5	10.1	4.3	44.6	59.0	0.0	2.3	0.9	0.8
1982	3	2	2	7	9.6	4.5	34.1	48.3	3.1	4.4	0.6	1.4
1983	1	0	4	5	10.7	4.8	35.3	50.9	0.9	0.0	1.1	1.0
1984	2	0	3	5	11.8	5.7	3[illegible].0	54.5	1.7	0.0	0.8	0.9
1985	1	0	1	2	12.1	6.1	37.2	55.4	0.8	0.0	0.3	0.4
Total, 64-85	33	7	40	80	216.2	62.3	868.2	1146.7				
Total, 75-85	14	6	29	49	114.0	46.4	482.5	643.0				
Mean, 64-85	1.5	0.3	1.8	3.6	9.8	2.8	39.5	52.1	1.527	1.123	0.461	0.698
Mean, 75-85	1.3	0.5	2.6	4.5	10.4	4.2	43.9	58.5	1.228	1.292	0.601	0.762

1/ See Appendix A

2/ Source: Reference 19 (adjusted by APO-220 for recategorization by user class)

2. Forecasted Annual Aircraft Operations ($ANNOPS_{c,y}$)

Air traffic activity, as measured by aircraft operations is one of two accident exposure factors used to quantify site-specific safety benefits. Site-specific activity forecast inputs have been developed by APO's Forecast Branch (Reference 15). These annual activity projections are considered over the assumed 20 year life-cycle of the candidate wind shear detection systems.

3. Safety Weather Exposure Factor (SWEF)

The discussion in Chapter I suggests that a strong relationship exists between the presence of microbursts and wind shear. Consequently, weather (specifically microbursts) is the second exposure factor used to quantify site-specific safety benefits. This safety weather exposure factor is defined as:

$$\text{SWEF} = \frac{\text{Site-Specific Annual Microbursts}}{\text{National Average Annual Microbursts Per Site}}$$

Estimates of the number of microbursts have been developed for all FAA-towered sites based on the relationship between microbursts and thunderstorm days at a given site. These estimates, as well as site-specific safety weather exposure factors, have been developed under the System Engineering and Integration Contract (SEIC) for FAA's System Engineering Service (Reference 6).

4. System Safety Effectiveness: Fraction of Avoidable Accidents ($SEFF_s$)

The fraction of accidents that are avoidable by a wind shear detection system is the system's safety effectiveness. Specifically, safety effectiveness is defined as the system's ability to detect hazardous wind shear phenomena and provide sufficient warning of such weather phenomena to pilots to prevent a wind shear accident.

Four attributes have been used to develop a system safety effectiveness metric:

- **Detection** - the ability to correctly identify terminal area wind shear phenomena.
- **Timeliness** of detection and warning with respect to the occurrence of a wind shear event.
- **Intensity** - the ability to provide accurate information on the strength or magnitude of the wind shear relative to operational runways.
- **Location** - the ability to accurately report wind shear phenomena's position with respect to its impact on terminal airspace.

System safety effectivities have been developed under the SEIC for FAA's System Engineering Service, and are presented in Table III-2, on a regional basis (Reference 6). Effectivity regions are defined in Appendix B.

TABLE III-2. Wind Shear System Safety Effectivities
(Fraction of Avoidable Accidents by System)

	Region				
System	E/NE	SE	M/SW	R/H	WC/T
Airborne*	0.55	0.55	0.55	0.55	0.55
LLWAS-6	0.10	0.10	0.10	0.10	0.10
LLWAS-EN	0.49	0.48	0.49	0.48	0.48
TDWR	0.79	0.80	0.78	0.76	0.80
ASR	0.55	0.63	0.51	0.47	0.63
TDWR+LLWAS-EN	0.84	0.85	0.84	0.84	0.85
ASR+LLWAS-EN	0.71	0.74	0.69	0.69	0.74
TDWR+ASR	0.83	0.86	0.81	0.79	0.86
TDWR+ASR+LLWAS-EN	0.89	0.90	0.88	0.86	0.90

Regions

E/NE	East/Northeast
SE	Southeast
M/SW	Midwest/Southwest
R/H	Rocky Mountain/High Plains
WC/T	West Coast/Tropical (Hawaii, Caribbean)

*See Chapter V for sensitivity analysis

Source: Reference 6

5. Expected Cost of a Wind Shear Accident ($ACCOST_c$)

The estimated cost of a wind shear accident is a function of the number and value of human injury (both fatal and nonfatal) and aircraft damage associated with the accident. $ACCOST_c$, the expected site-specific cost of a wind shear accident by user class (c), is derived below.

$$ACCOST_c = \overbrace{\{OCC_c \times ((PFAT_c x VLIF) + (PSINJ_c x CSINJ) + (PMINJ_c x CMINJ))\}}^{\text{Personal Injuries (Fatal, Serious, Minor)}} + \overbrace{\{(PDEST_c x CDEST_c) + (PSDAM_c x CSDAM_c) + (PMDAM_c x CMDAM_c)\}}^{\text{Aircraft Damage}}$$

$CDEST_c$:	DEFINITION:	Replacement cost of a destroyed aircraft by user class "c"
	VALUE:	Varies
	SOURCE:	Reference 16 and ADA Critical Value file
$CMDAM_c$:	DEFINITION:	Restoration cost of a minorly-damaged aircraft by user class "c"
	VALUE:	None (due to relative insignificance)
CMINJ:	DEFINITION:	Cost of a minor injury
	VALUE:	$2,300
	SOURCE:	Reference 16
$CSDAM_c$:	DEFINITION:	Restoration cost of a substantially-damaged aircraft by user class "c"
	VALUE:	Varies
	SOURCE:	Reference 16 and ADA Critical Value file
CSINJ:	DEFINITION:	Cost of a serious injury
	VALUE:	$640,000
	SOURCE:	APO-220 based on Reference 17
OCC_c:	DEFINITION:	Number of occupants by user class "c"

	VALUE:	Varies
	SOURCE:	ADA Critical Value File
$PDEST_c$:	DEFINITION:	Probability of an aircraft being destroyed in a wind shear accident by user class "c"
	VALUE:	Varies
	SOURCE:	Appendix
$PFAT_c$:	DEFINITION:	Probability of a fatality per occupant in a wind shear accident by user class "c"
	VALUE:	Varies
	SOURCE:	Appendix
$PMDAM_c$:	DEFINITION:	Probability of an aircraft being minorly-damaged in a wind shear accident by user class "c"
	VALUE:	Varies
	SOURCE:	Appendix
$PMINJ_c$:	DEFINITION:	Probability of a minor injury per occupant in a wind shear accident by user class "c"
	VALUE:	Varies
	SOURCE:	Appendix
$PSDAM_c$:	DEFINITION:	Probability of an aircraft being substantially damaged in a wind shear accident by user class "c"
	VALUE:	Varies
	SOURCE:	Appendix
$PSINJ_c$:	DEFINITION:	Probability of a serious injury per occupant in a wind shear accident by user class "c"
	VALUE:	Varies
	SOURCE:	Appendix
VLIF:	DEFINITION:	Value of a statistical life
	VALUE:	$1,500,000
	SOURCE:	Reference 17

C. Efficiency Benefits

1. Overview

Wind shift lines can make it necessary to shift runways in operation so that landing and departing aircraft can continue to operate into the wind with acceptable crosswinds. Airport traffic control tower (ATCT) watch supervisors are responsible for planning and timing these runway changes. Currently, LLWAS-6, PIREPs, and weather reports are the information sources for runway shifts. Although these sources of information are valuable, they provide a limited "picture" of the wind features in the vicinity of the airport. At the request of the FAA, a Doppler radar research project was conducted at Denver Stapleton International Airport by the National Center for Atmospheric Research (NCAR) during the summer of 1984. Findings of this research indicated that Doppler radar-generated gust front advisories can make planning for runway changes much more efficient. The documented results of this research project provide a point of departure for quantifying the efficiency benefits provided by the wind shear detection systems considered in the current effort.

2. The Microburst Advisory Service Project

On May 31, 1984, a Boeing 727 aircraft encountered a wind shear on takeoff roll and lift-off from Stapleton International Airport that resulted in the aircraft striking an instrument landing system antenna approximately 1100 feet beyond the end of the runway. The aircraft returned safely to the airport and was found to have two gashes in its fuselage. NCAR, which at times operates one or more Doppler weather radar units in the vicinity of Stapleton for meteorological research, verified that the aircraft had encountered a microburst. Based on this incident and the results of the 1982 NCAR Joint Aviation Weather Study (JAWS) Project, which showed microbursts to be a common feature in the Denver area during the thunderstorm season, the FAA requested that NCAR use one of its Doppler weather radars to set up and operate a microburst advisory service for the Stapleton control tower during the 1984 thunderstorm season. NCAR had the service in operation by early July. The service was named Classify, Locate, and Avoid Wind Shear (CLAWS). The service remained in operation for a six-week period during the peak of Denver's 1984 thunderstorm season.

During the course of the project, microburst advisories were issued to pilots on final approach, awaiting takeoff clearance, and on initial takeoff climb. In addition to microbursts, NCAR found another low-altitude wind shear phenomenon of operational significance to aviation and air traffic control - the wind shift line (e.g., gust front).

Early in the six week operating period, NCAR radar meteorologists noticed that they could clearly see gust fronts and other wind shift lines approaching and passing over Stapleton. After some experimentation, NCAR initiated an informal "gust front" advisory service for these wind shift lines. NCAR would verbally advise the ATCT watch supervisor of the expected time of arrival of the wind shift line at the Stapleton LLWAS centerfield sensor and its estimated maximum strength and direction. These advisories were informal in

that each watch supervisor was free to ignore, test, or use the advisories. After a confidence-building period in which the advisories were informally evaluated by the watch supervisors, the advisories began to be used operationally. The use of these advisories were solely for runway management purposes. They were not used to advise landing and departing pilots of potential wind shear encounters, which was beyond the resources of the project.

NCAR issued advisories for nearly 30 of the 32 wind shift lines observed nearing Stapleton over the six-week period. An unknown number of these advisories were used in support of operations. The watch supervisors found that the gust front advisories provided a relatively clear, accurate, timely, and reliable picture of approaching wind lines. The data set collected for these advisories indicated the following:

- Advisory lead times ranged from 3 to 50 minutes and averaged 17 minutes, consistent with Air Traffic's request for 20 minute lead times. NCAR personnel felt that they had the capability of providing significantly longer lead times.

- Estimated time of arrival accuracy ranged from perfect to as much as 10 minutes off with an average error of 4 minutes.

- Estimated maximum wind strength accuracy ranged from perfect to as much as 19 knots off with an average error of 7 knots.

Based on these results and consensus opinion of the watch supervisors, it was concluded that the advisories greatly enhanced both the planning and timing of runway shifts (i.e., selecting the new runway configuration and determining when the shift should be started). These advisories enabled the watch supervisors to:

- Move traffic into place on the new runway configuration in anticipation of the arrival of a wind shift line, reducing traffic disruption and increasing runway utilization;

- Reduce/eliminate the need for a second runway shift due to the incorrect selection of the appropriate runway configuration the first time (operationally called "chasing the winds"); and

- Reduce/eliminate unnecessary runway shifts where the watch supervisor finds out after the fact that the actual wind conditions did not warrant a runway change (e.g., the anticipated wind strength that led to the runway shift either did not occur or was of such short duration that it had no operational impacts).

Elimination of these three problems translates into potential efficiency benefits that can be attributed to a Doppler-based runway management product. In an attempt to quantify these potential benefits, follow-up interviews were conducted with the three Stapleton watch supervisors. Based on these discussions, a methodology was hypothesized for estimating the potential annual efficiency benefits and <u>first-cut</u> delay estimates were calculated for

Stapleton for 1984. The methodology and estimates are outlined in Table III-3. Except for delay costs per minute, all values presented in the table are averages of estimates given by the three Stapleton watch supervisors.

As illustrated in Table III-3, the annual delay benefits are expressed as the product of the potential cost avoidance per affected runway shift (Columns B through L) for each of the three runway shift problems and the estimated number of times each type of shift occurs during the course of a year (Columns M through O). The potential cost avoidance per affected runway shift (Columns J through L) is expressed as the product of the typical demand (number of departures/arrivals in queue) (Columns B and C), times delay per aircraft operation (Columns D through G), and the cost per aircraft delay minute (excluding value of passengers' time). Based on the expected annual frequency of each of these three problems, the estimated annual number of runway shifts, and the potential cost avoidance per affected runway shift, annual delay cost avoidance at Stapleton during 1984 was approximately $877,000.

3. Efficiency Benefits Algorithm

The methodology described above has been used as a foundation for quantifying efficiency benefits provided by candidate wind shear detection systems. The algorithm used to estimate site-specific efficiency benefits as well as mnemonic definitions are presented in Figure III-2. Descriptions of key variable inputs to the efficiency benefits algorithm are discussed below.

a. Forecasted Annual Aircraft Operations ($ANNOPS_{c,y}$)

Similar to the safety benefits, air traffic activity (measured by aircraft operations) is one of two exposure factors used to quantify site-specific efficiency benefits. Site-specific activity forecast inputs have been developed by APO's Forecast Branch (Reference 15). These annual activity projections are considered over the assumed 20 year life-cycle of the candidate wind shear detection systems.

b. Average Time Spent In Queue per Aircraft During Wind-Related Runway Shifts (QTM)

QTM, the average time spent by aircraft in queue during wind-related runway shifts, is projected to be 30 minutes for scheduled commercial users and 20 minutes for other users. These figures are based on average flight characteristics.

c. Average Delay per Aircraft Operation (DLOP)

DLOP, the average number of minutes of delay per aircraft operation during wind-related runway shifts, is estimated to be 5.0 minutes for all aircraft types and user classes, based on a weighted average of the corresponding values in Table III-3.

TABLE III-3: Potential Annual Benefits of a Doppler Radar Runway Management Product at Denver Stapleton Airport

Potential Cost Avoidance per Affected Runway Shift

Runway Shift Problem and Situation	Typical Demand: Departures In Queue For Departure Runways	Typical Demand: Arrivals In Queue For Arrival Runways	Typical Delay Per Operation (Minutes): Departure Taxi Time To New Runway	Typical Delay Per Operation (Minutes): Arrival Flying Time To New Runway	Typical Delay Per Operation (Minutes): Time Associated With Lost Departure Slots	Typical Delay Per Operation (Minutes): Time Associated With Lost Arrival Slots	Cost Per Aircraft Delay Minute: Departures	Cost Per Aircraft Delay Minute: Arrivals	Potential Cost Avoidance per Affected Runway Shift: Departures	Potential Cost Avoidance per Affected Runway Shift: Arrivals	Potential Cost Avoidance per Affected Runway Shift: Total	Estimated Annual Nr. of Affected Runway Shifts: Gross Nr.	Estimated Annual Nr. of Affected Runway Shifts: %	Estimated Annual Nr. of Affected Runway Shifts: Net Nr.	Potential Annual Cost Avoidance (000's of 84 $)
(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)	(L)	(M)	(N)	(O)	(P)
CORRECT SHIFT BUT TIMING COULD BE IMPROVED															
Situation 1 *	10	12	8	8			30	50	2400	4800	7200	95	0.33	31	$223
Situation 2 **	10	12			4	3	30	50	1200	1800	3000	95	0.67	64	192
															$415
EXTRA SHIFT: 1ST SHIFT UNALIGNED WITH WIND - 2ND SHIFT NECESSARY															
Situation 1	10	12	8	8			30	50	2400	4800	7200	60	0.33	20	$144
Situation 2 **	10	12			4	3	30	50	1200	1800	3000	60	0.67	40	120
															$264
EXTRA SHIFT: SHIFT MADE THAT PROVED TO BE UNNECESSARY WHEN THE WINDS BECAME KNOWN															
Situation 1 *	10	12	8	8			30	50	2400	4800	7200	45	0.33	15	$108
Situation 2 **	10	12			4	3	30	50	1200	1800	3000	45	0.67	30	90
															$198
TOTAL												200			$877

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* SITUATION 1: Wind conditions are such that the remaining operations in queue for old runway configuration must proceed to new runway configuration.

** SITUATION 2: Wind conditions are such that the remaining operations in queue for old runway configuration can continue to use that configuration but lack of low-altitude wind information still results in lost arrival and departure runway slots.

Source: Reference 18

FIGURE III-2. Site-Specific Efficiency Benefits Algorithm

$$LCYEFF_s = \sum_{y=1}^{20} \{ ANNEFF_y \times (1 / (1 + d)^{y-0.5}) \}$$

$$ANNEFF_{s,y} = \sum_{c} \overbrace{\overbrace{\frac{ANNOPS_{c,y}}{365 \text{x} THR \text{x} 60/QTM}}^{\text{Typical Demand per Rwy Shift}} \times \overbrace{DLOP}^{\text{Min. of Delay per Opn.}} \times \overbrace{\left(\frac{AOC_c}{60}+\frac{PTM_c}{60}\right)}^{\text{Cost per Aircraft Delay Min.}}}^{\text{Cost Avoidance per Affected Runway Shift}} \times \overbrace{(DWEF \times DEFF_s)}^{\text{Annual Nr. of Avoidable Rwy Shifts}}$$

$LCYEFF_s$	=	Discounted present value of life-cycle efficiency benefits of system "s" (constant dollars)
s	=	System under consideration
y	=	Year of system's operating life-cycle (assumed to be 20 years)
$ANNEFF_{s,y}$	=	Nondiscounted value of expected annual efficiency benefits of system "s" in year "y" (constant dollars)
d	=	Discount rate. Set at 10 percent in accordance with OMB guidelines (Reference 14)
0.5	=	Exponential factor to effect mid-period discounting
$ANNOPS_{c,y}$	=	Forecasted annual number of aircraft operations by user class "c" in year "y"
THR	=	ATCT operating hours per day
QTM	=	Average time (in minutes) spent in queue per aircraft during wind-related runway shifts
DLOP	=	Average delay per aircraft operation (in minutes)
AOC_c	=	Hourly variable operating costs of aircraft by user class "c"
PTM_c	=	Hourly value of passengers' time multiplied by number of passengers
DWEF	=	Site-specific delay weather exposure factor
$DEFF_s$	=	Delay effectiveness of system "s"

d. Aircraft Variable Operating Costs (AOC_c)

Aircraft variable operating costs by user class (Reference 16).

e. Value of Passengers' and Occupants Time (PTM_c)

Hourly value of passengers' time multiplied by number of passengers for commercial users and multiplied by the number of occupants for noncommercial users. A distinction between passengers and occupants is made for this calculation, since crew are included in aircraft operating costs for commercial users and are excluded for noncommercial users (Reference 16).

f. Delay Weather Exposure Factor (DWEF)

The overview to the section on efficiency benefits suggests that a relationship exists between the number of gust fronts and the number of runway shifts at an airport. Consequently, weather (specifically gust fronts) is the second exposure factor used to quantify site-specific delay benefits. This delay weather exposure factor is defined as:

$$\text{DWEF} = \text{Site-Specific Annual Gust Fronts} \quad \times \quad \frac{\text{Runway Shifts}}{\text{Gust Front}}$$

Estimates of the number of gust fronts have been developed for all FAA-towered sites based on the relationship between gust fronts and thunderstorm days at a given site. These estimates, as well as site-specific delay weather exposure factors, have been developed under the SEIC for FAA's System Engineering Service (Reference 6).

g. System Delay Effectiveness: Fraction of Avertible Runway Shifts ($DEFF_s$)

The fraction of runway shifts that are avertible by a wind shear detection system is the system's delay effectiveness. Specifically, delay effectiveness is defined as the system's capability to detect meteorological conditions requiring change of active runway or terminal area approach/departure patterns, and to provide timely warning of such weather phenomena to air traffic controllers before it arrives at the airport. As with safety effectivities, four attributes have been used to develop a delay effectiveness metric: detection, timeliness, intensity, and location.

System delay effectivities have been developed under the SEIC for FAA's System Engineering Service, and are presented on a regional basis in Table III-4 (Reference 6). Note that airborne systems do not exhibit any delay effectiveness, so that this system type does not appear in Table III-4.

TABLE III-4. Wind Shear System Delay Effectivities
(Fraction of Avoidable Runway Shifts by System)

	Region				
System	E/NE	SE	M/SW	R/H	WC/T
LLWAS-6	0.08	0.07	0.09	0.08	0.08
LLWAS-EN	0.26	0.24	0.28	0.26	0.26
TDWR	0.72	0.78	0.66	0.59	0.66
ASR	0.49	0.56	0.42	0.35	0.44
TDWR+LLWAS-EN	0.75	0.80	0.70	0.64	0.70
ASR+LLWAS-EN	0.56	0.59	0.53	0.46	0.52
TDWR+ASR	0.75	0.80	0.70	0.64	0.70
TDWR+ASR+LLWAS-EN	0.78	0.82	0.74	0.69	0.74

Regions

E/NE	East/Northeast
SE	Southeast
M/SW	Midwest/Southwest
R/H	Rocky Mountain/High Plains
WC/T	West Coast/Tropical (Hawaii, Caribbean)

Source: Reference 6

D. Life-Cycle Benefits Summary

Life-cycle benefits are derived by first calculating a system's safety and efficiency benefit, respectively, for each year of the system's economic life (20 years), then discounting to present value, and summing. For estimating benefits, all factors other than annual aircraft activity are assumed to remain constant throughout the 20-year system life-cycle. Present value life-cycle benefits (BPV_s) of a wind shear system can be expressed as:

$$BPV_s = \sum_{y=1}^{20} (ANNSAF_{s,y} + ANNEFF_{s,y})/((1 + d)^{y-0.5})$$

where "y" is each year of an assumed 20 year economic life, "$ANNSAF_{s,y}$" is the safety benefit for system "s" in year "y", "$ANNEFF_{s,y}$' is the efficiency benefit of system "s" in year "y", "d" is the OMB-prescribed discount rate (10) percent, and 0.5 is the exponential factors to effect mid-period discounting.

CHAPTER IV - LIFE-CYCLE COSTS

Two types of costs are relevant to the analysis--nonrecurring costs and recurring costs. Each of these cost categories is described below:

- **Nonrecurring costs** are one-time expenditures associated with the acquisition of a system. These include the costs of designing, manufacturing, installing and planning for the operation and support of a wind shear system. Nonrecurring costs are comprised of research & development (R&D) and facilities & equipment (F&E) expenditures. Within this category, only F&E wind shear system costs are considered in Chapter V - Results.

- **Recurring costs** are expenditures for operations and maintenance during a system's life cycle (assumed to be 20 years for wind shear systems). Recurring costs are comprised of operations and maintenance (O&M) expenditures.

Table IV-1 presents average unit 20-year-life-cycle costs for the wind shear detection systems evaluated in this report. These include F&E costs as well as O&M costs for each candidate system. The top half of the table presents respective cost figures for the candidate wind shear systems on a "stand-alone" basis, while the bottom half of the table presents cost figures for system integratio· The cost of an integrated system is equal to the sum of the respective component system costs and integration costs.

TABLE IV-1. Life-Cycle Costs

System	Average Unit Life Cycle Costs (000's of Nondiscounted 1989 $)
LLWAS-EN	
F&E	557
O&M	330
TDWR	
F&E	4,000
O&M	6,142
ASR (Modification)	
F&E	293
O&M	95
System Integration	
TDWR+LLWAS-EN	
F&E	217
O&M	65
ASR+LLWAS-EN	
F&E	240
O&M	55
TDWR+ASR	
F&E	490
O&M	209
TDWR+ASR+LLWAS-EN	
F&E	708
O&M	274

Source: Reference 6 and FAA program offices

CHAPTER V - RESULTS

A. Assumptions and Ground Rules

Several assumptions and ground rules (in addition to those presented in Chapter III) have been developed for applying the wind shear criteria to FAA towered sites. These assumptions and ground rules are highlighted below:

- Candidate airports for LLWAS-EN, TDWR, and LLWAS-EN+TDWR are all FAA towered sites.

- The criteria does **not** apply to the establishment of an ASR-9 site, but rather to wind shear modification of an existing (or planned) ASR-9. A total of 103 sites already scheduled to receive an ASR-9 are considered candidates for wind shear modification. Twenty-one ASR-9's have not been considered for modification for one or more of the following reasons: 1) the ASR-9 is for military use, 2) there are two ASR-9's at an airport, and 3) there are coverage gaps caused by obstacles or distance of the ASR from an airport.

- The LLWAS-6 is not considered as a candidate system at airports where it has not already been sited.

- No additional wind shear-related benefits are achieved by integrating an LLWAS-6 with a TDWR or modified ASR-9. Consequently, a site may have a "stand-alone" LLWAS-6 with a TDWR or modified ASR-9.

- For a site to receive more than one system (LLWAS-EN, TDWR, or modified ASR-9) only integrated systems are considered - no "side-by-side" systems are considered for these three wind shear system types.

- TDWR is considered part of the reference system at 44 sites under contract. TDWR's at three support sites are excluded from the analysis: the FAA Technical Center, the FAA Academy, and Andrews AFB.

- Where applicable, LLWAS-EN and TDWR are considered part of the reference system for ASR-9 modification sites. In other words, LLWAS-EN, TDWR, and LLWAS-EN integrated with TDWR are considered establishment candidates at ASR-9 sites first. Then wind shear modification of the ASR-9 is considered. This assumption is based on the later implementation schedule for ASR-9 modification relative to the implementation schedules for LLWAS-EN and TDWR.

- The analysis is conducted both including and excluding airborne systems. When included, airborne systems are considered part of the reference system.

- The system safety effectiveness of the airborne system is 55% (see results for sensitivity of this assumption). This level of safety effectiveness for airborne systems is required for benefits associated with these systems to exceed their costs (Reference 5). As stated in Chapter III, airborne systems do not have any system efficiency effectiveness.

- F&E costs associated with a reference system are considered "sunk" (zero).

- Average unit life-cycle O&M costs for the LLWAS-6 is $180,000 (non-discounted 1989 dollars) (Reference 20).

- All systems are evaluated over the 1990-2009 interval.

B. Criteria Results

The establishment criteria for wind shear detection systems have been applied to all FAA towered sites, in accordance with the assumptions and ground rules discussed above. Due to the uncertainty of the effectiveness of the airborne system, the criteria application has been applied both with and without the airborne system as a candidate system for wind shear detection.

1. Results With Airborne Systems

Tables V-1, V-1A, and V-1B present the results of the criteria application when airborne systems are included in the analysis. Each table considers the airborne system at a different level of safety effectiveness--55%, 82.5%, and 27.5%, respectively. These tables illustrate the relationship between the safety effectiveness of the airborne system and the total number of systems that result from the criteria application. In general, a higher airborne system safety effectiveness results in fewer total wind shear systems when applying the criteria. This is intuitive since the LLWAS-EN, TDWR, and modified ASR-9 systems are competing for the same set of benefits as the airborne systems. In this regard, introducing the airborne system at any accepted level of safety effectiveness will diminish the number of sites that qualify for competing systems as well as the total number of competing systems that result from criteria application.

2. Results Without Airborne Systems

Table V-2 presents the results of the criteria application when airborne systems are excluded from the analysis. The first part of the table displays the number of sites for each optimal wind shear system configuration. A total of 121 sites qualify for one or more wind shear detection systems under this scenario.

The second part of the table presents the total number of systems (either stand-alone or integrated) that result from the criteria application. A total of 179 systems result from application of the criteria without considering airborne systems.

TABLE V-1. Results With Airborne Systems*

Optimal System Configuration	Number of Sites
LLWAS-EN	3
TDWR	19
ASR	33
TDWR+LLWAS-EN	21
ASR+LLWAS-EN	5
TDWR+ASR	0
TDWR+ASR+LLWAS-EN	6
Site Total	87

Summary

System Configuration	Total Number of Systems
LLWAS-EN	36
TDWR	46
ASR	44
System Total	126

*Airborne System Safety Effectivity = 55%

TABLE V-1A. Results With Airborne Systems (High Effectivity Scenario)*

Optimal System Configuration	Number of Sites
LLWAS-EN	1
TDWR	18
ASR	18
TDWR+LLWAS-EN	20
ASR+LLWAS-EN	2
TDWR+ASR	0
TDWR+ASR+LLWAS-EN	6
Site Total	65

Summary

System Configuration	Total Number of Systems
LLWAS-EN	30
TDWR	44
ASR	26
System Total	100

*Airborne System Safety Effectivity = 82.5%

TABLE V-1B. Results With Airborne Systems (Low Effectivity Scenario)*

Optimal System Configuration	Number of Sites
LLWAS-EN	22
TDWR	19
ASR	16
TDWR+LLWAS-EN	21
ASR+LLWAS-EN	23
TDWR+ASR	0
TDWR+ASR+LLWAS-EN	6
Site Total	107

Summary

System Configuration	Total Number of Systems
LLWAS-EN	72
TDWR	46
ASR	45
System Total	163

*Airborne System Safety Effectivity = 27.5%

TABLE V-2. Results Without Airborne Systems

Optimal System Configuration	Number of Sites
LLWAS-EN	38
TDWR	19
ASR	12
TDWR+LLWAS-EN	21
ASR+LLWAS-EN	25
TDWR+ASR	0
TDWR+ASR+LLWAS-EN	6
Site Total	121

Summary

System Configuration	Total Number of Systems
LLWAS-EN	90
TDWR	46
ASR	43
System Total	179

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APPENDIX A. Aircraft Accidents and Incidents At FAA Towered Airports Related to Low-Altitude Wind Shear

	NTSB File Number	Date	Location	St	LOC	Aircraft Type	Flight Phase Ldg	T/O	Distance from Rwy =< 1 Mi.	> 1 Mi.	Injuries Fat	Ser	Min	None	Tot	Aircraft Damage Dest	Sub'l Dmg	Minor Dmg	No Dmg
AC	1-0038	01-Jul-64	New York	NY	JFK	B720B			X		0	0	0	12	12		S		
AC	1-0064	24-Dec-64	San Francisco	CA	SFO	L1049H		T/O		X	3	0	0	0	3	D			
AC	1-0014	17-Mar-65	Kansas City	MO	MCI	B727	Ldg		X		0	0	0	97	97		S		
GA	3-3625	24-Dec-65	Oklahoma City	OK	OKC	BEB55	Ldg		X		0	0	0	4	4		S		
AC	1-0003	23-Jan-66	New York	NY	JFK	B707-227	Ldg		X		0	0	0	136	136		S		
AC	1-0018	27-Feb-66	New Orleans	LA	MSY	DC8-33	Ldg		X		0	0	0	97	97		S		
GA	3-1280	08-May-66	Herndon	VA	IAD	BEB95	Ldg		X		0	0	0	4	4		S		
GA	3-2414	11-Aug-66	Denver	CO	DEN	BE A-35		T/O	X		0	0	0	4	4		S		
GA	3-2064	13-Aug-66	Oklahoma City	OK	OKC	NAV NA-1	Ldg		X		0	0	0	4	4		S		
AT	3-2602	29-Jul-67	Hilo	HI	ITO	DH104	Ldg		X		0	0	0	13	13		S		
GA	3-0100	24-Jan-68	Greensboro	NC	GSO	C310	Ldg		X		0	0	0	3	3		S		
AC	1-0025	08-Jun-68	Salt Lake City	UT	SLC	B-727	Ldg		X		0	1	3	88	92		S		
GA	3-4445	[illegible]-Dec-68	Chicago	IL	CGX	BEA65	Ldg		X		0	0	0	4	4		S		
GA	3-2061	30-Jun-69	Palo Alto	CA	PAO	PA-28	Ldg		X		0	0	0	2	2		S		
GA	3-2101	10-Jul-69	Rapid City	SD	RAP	PA-28-180		T/O	X		0	0	0	4	4		S		
GA	3-0617	02-Apr-70	Raleigh	NC	RDU	C401A	Ldg		X		5	0	0	0	5	D			
AC	1-0050	10-Dec-70	St. Thomas	VI	STT	CV640	Ldg		X		0	0	10	10	20		S		
AC	3-0001	04-Jan-71	New York	NY	LGA	DC3C	Ldg		X		0	2	0	0	2	D			
AC	1-0002	18-May-72	Ft Lauderdale	FL	FLL	DC9	Ldg		X		0	3	0	7	10	D			
AC	4-0030	26-Jul-72	New Orleans	LA	MSY	B727	Ldg		X		0	0	0	62	62			M	
GA	3-2852	04-Aug-72	Montgomery	AL	MGM	CESS 210F	Ldg		X		0	0	0	4	4		S		
GA	3-4058	26-Nov-72	Memphis	TN	MEM	PA30	Ldg		X		0	1	0	0	1	D			
AC	1-0047	12-Dec-72	New York	NY	JFK	B707	Ldg		X		0	0	0	3	3		S		
AC	1-0005	03-Mar-73	Wichita	KS	ICT	B727	Ldg		X		0	0	3	64	67		S		
AC	4-0032	15-Jun-73	Chicago	IL	ORD	DC8	Ldg		X		0	0	0	3	3			M	
AC	1-0041	23-Jul-73	St. Louis	MO	STL	FH227B	Ldg		X		38	6	0	0	44	D			
AC	1-0019	28-Oct-73	Greensboro	NC	GSO	B737	Ldg		X		0	0	5	91	96		S		
AC	1-0028	27-Nov-73	Chattanooga	TN	CHA	DC9	Ldg		X		0	4	38	37	79		S		
AC	A-0004	17-Dec-73	Boston	MA	BOS	DC10	Ldg		X		0	3	13	151	167		S		
AC	1-0001	30-Jan-74	Pago Pago	SA	TUT	B707	Ldg		X		96	5	0	0	101	D			
AC	4-0022	14-Dec-74	Houston	TX	IAH	B727	Ldg		X		0	0	0	38	38			M	
GA	3-1005	20-Feb-75	Opa Locka	FL	OPF	BE95-55	Ldg		X		0	0	0	1	1		S		

	NTSB File Number	Date	Location	St	LOC	Aircraft Type	Flight Phase: Ldg	Flight Phase: T/O	Distance from Rwy: =< 1 Mi.	Distance from Rwy: > 1 Mi.	Injuries: Fat	Injuries: Ser	Injuries: Min	Injuries: None	Injuries: Tot	Aircraft Damage: Dest	Aircraft Damage: Sub'l Dmg	Aircraft Damage: Minor Dmg	Aircraft Damage: No Dmg
AC	1-0006	24-Jun-75	New York	NY	JFK	B727	Ldg		X		112	12	0	0	124	D			
GA	3-1865	11-Jul-75	Dallas	TX	ADS	Grumman G159	Ldg		X		0	0	0	9	9		S		
AC	1-0012	07-Aug-75	Denver	CO	DEN	B727		T/O	X		0	15	0	119	134		S		
GA	3-2161	16-Aug-75	Alexandria	LA	ESF	PA23	Ldg		X		0	0	1	0	1	D			
GA	3-2309	27-Aug-75	Denver	CO	BJC	Beech B19	Ldg		X		0	0	0	2	2		S		
AC	1-0022	12-Nov-75	Raleigh	NC	RDU	B727	Ldg		X		0	1	7	131	139		S		
AC	4-0020	29-Nov-75	St. Louis	MO	STL	DC9	Ldg		X		0	0	0	32	32			M	
AC	4-0031	31-Dec-75	Greer	SC	GSP	DC9-31	Ldg		X		0	0	0	31	31			M	
AC	1-0011	23-Jun-76	Philadelphia	PA	PHL	DC-9	Ldg		X		0	86	0	20	106	D			
GA	3-4055	21-Dec-76	White Plains	NY	HPN	Cessna 182	Ldg		X		0	0	0	1	1		S		
AC	1-0022	03-Jun-77	Tucson	AZ	TUS	B-727		T/O	X		0	0	0	91	91		S		
GA	3-3227	14-Dec-77	Groton	CT	GON	Learjet 35	Ldg			X	0	0	0	3	3		S		
AT	3-4433	14-Mar-78	Pontiac	MI	PTK	Beech D18	Ldg		X		2	0	0	0	2	D			
GA	3-2675	16-Jul-78	Colorado Springs	CO	COS	Piper PA-28		T/O	X		0	1	1	2	4		S		
GA	3-2754	21-Aug-78	Denver	CO	BJC	Cessna 150	Ldg		X		0	2	0	0	2		S		
GA	3-3517	24-Sep-78	Santa Barbara	CA	SBA	Cessna 182-M	Ldg		X		2	0	0	0	2	D			
AT	3-0861	19-Jan-79	Grand Rapids	MI	GRR	Aerostar 601	Ldg		X		4	2	0	0	6	D			
GA	3-0879	22-Feb-79	Kansas City	MO	MKC	Cessna 421-A	Ldg			X	3	0	0	0	3	D			
GA	3-1541	01-Jul-79	Denver	CO	APA	Piper PA28R		T/O	X		0	0	0	4	4		S		
GA	3-3041	23-Dec-79	Monterey	CA	MRY	Beech 65-90		T/O	X		0	0	0	1	1		S		
GA	3-0561	14-Feb-80	Houston	TX	IAH	Mitsubishi MU-2B	Ldg		X		4	1	0	0	5	D			
GA	3-0111	17-Feb-80	Fairbanks	AK	FAI	Cessna 180	Ldg		X		0	0	0	2	2		S		
AT	3-3517	07-Jul-80	Jackson	MS	JAN	Aero Comdr 680V	Ldg			X	1	1	0	0	2	D			
GA	3-2789	06-Aug-80	Kodiak	AK	ADQ	Piper PA-18	Ldg			X	0	0	1	1	2		S		
GA	3-0701	04-Feb-81	Wilmington	DE	ILG	Piper PA-28	Ldg		X		0	0	0	2	2		S		
AT	3-3443	10-Feb-81	Houma	LA	HUM	Cessna 310R	Ldg			X	4	0	0	0	4	D			
GA	3-1801	11-Feb-81	White Plains	NY	HPN	Lockheed 1329	Ldg			X	8	0	0	0	8	D			
GA	3-2042	16-Aug-81	Tuscaloosa	AL	TCL	Piper PA-32	Ldg		X		0	1	1	0	2	D			
GA	3-2288	23-Aug-81	Prescott	AZ	PRC	Cessna 210		T/O	X		0	0	0	4	4		S		
AT	2612	05-Jan-82	Ithica	NY	ITH	Piper PA-31	Ldg			X	2	0	0	0	2	D			
AT	1854	01-Feb-82	Groton	CT	GON	Beech 99	Ldg		X		0	5	2	0	7	D			
GA	137	15-Feb-82	San Juan	PR	SJU	Cessna 172	Ldg		X		0	0	0	1	1		S		
AC	5106	21-May-82	Dayton	OH	DAY	BAC111	Ldg		X		0	0	0	48	48				N
AC	3148	09-Jul-82	New Orleans	LA	MSY	B-727		T/O	X		153	9	0	7	169	D			
GA	2543	28-Oct-82	McAllen	TX	MFE	Piper PA-28	Ldg		X		0	0	0	2	2		S		
AC	5111	05-Dec-82	Winston-Salem	NC	INT	B737	Ldg		X		0	0	0	5	5			M	
GA	1024	30-Mar-83	Aspen	CO	ASE	Stinson 108-2	Ldg		X		0	0	1	2	3		S		

	NTSB File Number	Date	Location	St	LOC	Aircraft Type	Flight Phase: Ldg	Flight Phase: T/O	Distance from Rwy: =< 1 Mi.	Distance from Rwy: > 1 Mi.	Injuries: Fat	Injuries: Ser	Injuries: Min	Injuries: None	Injuries: Tot	Aircraft Damage: Dest	Aircraft Damage: Sub'l Dmg	Aircraft Damage: Minor Dmg	Aircraft Damage: No Dmg
GA	583	05-Jun-83	Pittsburgh	PA	AGC	Beech 77	Ldg			X	0	0	0	1	1		S		
GA	2978	11-Oct-83	Dallas	TX	ADS	Cessna 152	Ldg			X	0	0	0	2	2	D			
GA	1956	21-Nov-83	Farmingdale	NY	FRG	Piper PA28	Ldg			X	0	0	0	1	1		S		
AC	3297	28-Dec-83	New York	NY	LGA	B727	Ldg		X		0	0	0	127	127		S		
GA	574	05-Apr-84	Binghamton	NY	BGM	T303	Ldg		X		0	0	0	1	1		S		
AC	2563	31-May-84	Denver	CO	DEN	B727		T/O	X		0	0	0	105	105		S		
AC	1976	13-Jun-84	Detroit	MI	DTW	DC9	Ldg		X		0	0	10	46	56		S		
GA	3260	06-Dec-84	Chino	CA	CNO	Stinson 108-2	Ldg		X		0	0	1	0	1		S		
GA	3164	22-Dec-84	Rochester	NY	ROC	Cessna 402B		T/O	X		1	0	0	0	1	D			
GA	833	03-May-85	Seattle	WA	BFI	Piper PA-32	Ldg		X		3	0	0	0	3	D			
AC	1572	02-Aug-85	Dallas-Ft Worth	TX	DFW	L1011	Ldg			X	135	15	13	2	165	D			
	Tot, 64-85	80					68	12	68	12	576	176	110	1748	2610	26	47	6	1
	Pct, 64-85						85%	15%	85%	15%	22%	7%	4%	67%		33%	59%	8%	1%
	Tot, 75-85	49					40	9	38	11	434	151	38	806	1429	19	26	3	1
	Pct, 75-85						82%	18%	78%	22%	30%	11%	3%	56%		39%	53%	6%	2%
	INCIDENTS:																		
AC	1-0006	24-Jun-75	New York	NY	JFK	L-1011	Ldg		X		0	0	0	na	na	na	na	na	na
AC	na	22-Aug-79	Atlanta	GA	ATL	B-727	Ldg		X		0	0	0	na	na	na	na	na	na
AC	5087	28-Jul-82	New York	NY	LGA	B-727	Ldg		X		0	0	0	129	129			M	

Source: References 3, 7, 8, 11, 12, 13 and NTSB Aviation Accident Data System

APPENDIX B. Effectivity Regions for States and Territories

State/Territory	Effectivity Region	State/Territory	Effectivity Region	State/Territory	Effectivity Region
Alabama	S	Kentucky	S	Ohio	M
Alaska	W	Louisiana	S	Oklahoma	M
American Samoa	W	Maine	E	Oregon	W
Arizona	H	Maryland	E	Pennsylvania	E
Arkansas	S	Massachusetts	E	Puerto Rico	W
California	W	Michigan	M	Rhode Island	E
Colorado	H	Minnesota	M	South Carolina	S
Connecticut	E	Mississippi	S	South Dakota	M
Delaware	E	Missouri	M	Tennessee	S
District of Columbia	E	Montana	H	Texas (see below)	H,M,S
Florida	S	Nebraska	M	Trust Territories	W
Georgia	S	Nevada	H	Utah	H
Guam	W	New Hampshire	E	Vermont	E
Hawaii	W	New Jersey	E	Virginia	E
Idaho	H	New Mexico	H	Virgin Islands	W
Illinois	M	New York	E	Washington	W
Indiana	M	North Carolina	S	West Virginia	S
Iowa	M	North Dakota	H	Wisconsin	M
Kansas	M	Norther Mariana Is.	W	Wyoming	H

Texas		Texas		Texas	
ELP	H	ABI	M	AUS	S
		ACT	M	BPT	S
		ADS	M	BRO	S
		AMA	M	CLL	S
		DAL	M	CRP	S
		DFW	M	DWH	S
		FTW	M	GGG	S
		LBB	M	HOU	S
		MAF	M	HRL	S
		RBD	M	IAH	S
		SJT	M	MFE	S
		TYR	M	SAT	S
				SSF	S

Effectivity Regions

E - East/Northeast
S - Southeast
M - Midwest/Southwest
H - Rocky Mountain/High Plains
W - West Coast/Tropical